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CORRELATION OF COMPRESSIVE AND SHEAR STRESS WITH SPALLING OF PLASMA SPRAYED CERAMIC MATERIALS

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SUMMARY

Ceramics on metal substrates for potential use as high temperature seals or other applications are exposed to forces originating from differences in thermal expansion between the ceramic and the metal substrate. The associated stresses produce spalling in ceramics, e.g., plasma sprayed ZrO_2-Y_2O_3, Al_2O_3-TiO_2, and porcelain enamel. The off-axis effect of compression forces resulting from high temperature plastic flow of the ceramic producing buckling of the ceramic is developed. An estimate of shear stress is made. Shear is associated with the edge or boundary stresses on the component while bending is associated with the distortion of an interior region. Both modes are significant in predicting life of the ceramic.

INTRODUCTION

In order to conserve fuel and secure higher performance it is desired to increase the thermodynamic efficiency of gas turbine engines. Development of

improved gas passage seals is a practical way of achieving these objectives. Ceramic and metal combinations are promising potential materials for construction of an extended temperature, high performance and reliable gas passage seal. Before any credeance can be assigned to the development of a turbine engine component of high reliability, it is essential that the properties, characteristics, behavior, and interactions of the component be understood so that componenent reliability can be predicted.

Other work (refs. 1 and 2) has shown that there are sources of differential stresses between plasma sprayed ceramics and the supporting structures. There appear to be two modes of failure, those associated with specimens where edge delamination occurs (shear) and those associated with bending and delamination of regions near the central portion of the ceramic or where edge effects are not significant (pulloff). The question becomes, under what conditions are these failure modes important and why?

This study of stress origins and resultants is made in order to define the interaction forces between ceramics and supporting metal structures and answer this question.

SHEAR FAILURE

Shear due to Thermal Expansion

Many of the ceramics of interest for high temperature applications in gas turbine engines have lower thermal expansion coefficients than the metal substrates used as support. For this analysis, the assumption is made that the metal and the plasma sprayed ceramic material in the seal combination or other application, are in equilibrium at ambient temperature, no matter how the ceramic is placed on the metal substrate.

As the metal substrate (cobalt or nickel super alloys) and attached ceramic (ZrO_2-Y_2O_3) combination are heated the differential expansion

$$\Delta \ell = \Delta \alpha \ \Delta T \ \ell \tag{1}$$

gives rise to a size effect of the piece on the stress in the plasma sprayed ceramic.

Shear will be produced in the ceramic and substrate interface with tension in the ceramic. A simple force balance, illustrated in figure 1, can be written

$$-\tau \ dx + \Delta\sigma \ dy = 0 \tag{2}$$

subject to the boundary conditions:

$$\sigma(-L) = \sigma(L) = 0 \tag{3}$$

The shear stress becomes largest near the edge of the specimen and can provoke delamination whenever the allowable shear stress is exceeded.* Considering only the region x -> L, equation (2) may be approximated as (fig. 1)

$$\frac{t\sigma_t}{\tau(\ell - x)} = 1 \tag{4}$$

*Edges and corners are stress concentrators and notches can also provide cracking which is aggravated by the increased shear due to thermal expansion (contraction).

Assuming σt is only due to thermal effects, the delamination length becomes

$$(\ell - x) = \frac{\Delta\alpha \; \Delta T \; Et}{\tau} \tag{5}$$

If the ceramic shears from the substrate (delaminates) due to the differential thermal expansion, then upon return to ambient temperature the ceramic and metal substrate will have the same length. If the tensile strength of the ceramic is exceeded before the critical shear stress is reached, then the stress will be relieved by cracking of the ceramic and it will not separate from the substrate by shear. Figure 2 shows stress originating from physical deformation rather than from thermal expansion can cause cracking of the ceramic without separation. The length of the ceramic between cracks (w) was measured and expressed in terms of the ceramic (ZrO_2-Y_2O_3) thickness (t) as,

$$W = 0.51 + 0.113\ t^2 \tag{6a}$$

$$0.12 < t < 1 \text{ mm}$$

or

$$W = 0.02 + 73\ t^2 \tag{6b}$$

$$0.005 < t < 0.040 \text{in.}$$

If however the thickness of the ceramic becomes sufficiently large, the tensile force is spread over a larger area until a point is reached where the unit tensile stress is below the tensile rupture strength of the ceramic and at this stress level shear of the ceramic from the substrate will always occur. From our bending tests, this maximum tensile stress is less than 1800 psi (ref. 3).

For such uses as mechanical or thermal protection, but not corrosion, it is adequate to design for cracking of the plasma sprayed material and thereby avoid catastrophic shear separation.

Shear due to Thermal Contraction

In the above discussion, the substrate and attached ceramic combination was assumed to be thermally isoelastic up to 1000° C. This behavior is essentially characteristic of single oxide component ceramics or of mixed oxide ceramics which have been homophased by thermal equilibration, provided the oxides are not pronounced glass formers (ref. 4). However, it has been previously shown that the ceramic systems of ZrO_2-Y_2O_3, ZrO_2-CaO or Al_2O-TiO_2 which are of particular interest for gas turbine use for high temperature seals or other applications are extremely plastic at high temperatures after these particular ceramics have been plasma sprayed (ref. 5).

On return to ambient the plastic flow is not reversed due to aging or devitrification at temperature and the ceramic which is stretched at temperature by the metal substrate will be elastically compressed by the metal substrate on return to ambient. The tensile force on the metal substrate and compressive force on the ceramic will be in balance, equations (1) to (3). Again for a thick metal substrate and uniform heating, bending will be small and the shear stress which is zero at the center line of the bar specimen increases with increasing dimension of the part.

When the ceramic shears from the substrate after the sample has been raised to temperature and returned to ambient, the ceramic is longer than the substrate. If shear resulted from tension on the ceramic at temperature the length of the ceramic and the substrate would be the same when returned to ambient. Since the former was observed to be true, it indicates that plastic flow occured at high temperature an shear occurred in compression on return to ambient conditions.

However, the growth in the ceramic is only approximately 50-percent of that expected from the thermal expansion between the ceramic and the metal substrate. This is the strain which produces shear. Therefore it follows that the shear stress which results from plastic flow at high temperature is only approximately 50 percent of the shear stress which would be experienced by an elastic ceramic at temperature.

Thus it is apparent that plasma sprayed materials on large specimens can fail by shear, and in particular near edge boundaries and corners.

PULLOFF FAILURE

Bending Stress due to Thermal Contraction

Excessive compressive loads on the coating can occur during the heating transient and from nonlinear behavior such as creep upon return to ambient conditions or from these combined loads. We now want to investigate the possibility of ceramic pulloff failures due to excessive compressive loads.

Model

We will assume the ceramic to be loaded in compression as to develop end moments which tend to bend the coating away from the substrate as illustrated in figure 2. The adhesive/cohesive forces resist this applied moment to the point of pulloff where the ceramic fails. The energy of this system may be written per unit width as,

$$\int_0^L \left[\frac{EI}{2}\left(\frac{\partial^2 W}{\partial x^2}\right)^2 + \frac{\beta W^2}{2}\right] dx = \frac{Pt}{2}\frac{\partial w}{\partial x}\bigg|_{x=0} - \frac{Pt}{z}\frac{\partial w}{\partial x}\bigg|_{x=L} \qquad (7)$$

where w is the deflection of the coated system, EI the stiffness of the ceramic, B the elastic modulus of the substrate and P the load applied to the ceramic along the neutral axis to produce the moment $Pt/2$. Assuming that the deflection w may be approximated by a sine function*

$$w = a_1 \sin\left(\frac{\pi x}{L}\right) \tag{8}$$

the solution for a_1 becomes

$$a_1 = \pi P\left(\frac{t}{L}\right)\left[\frac{EI\pi^4}{4L^3} + \frac{\beta L}{4}\right]^{-1} \tag{9}$$

We further assume that the maximum deflection will occur at $x = L/2$ with the adhesive/cohesive stress related to the substrate stiffness-deflection product

$$Bw_{max} = \sigma_p \tag{10}$$

and

$$P = t\sigma_c \tag{11}$$

The previous expression now becomes, see also figure 3,

$$\frac{\sigma_c^*}{\sigma_p}\left(\frac{t}{L}\right)^2 = \frac{Pt}{\sigma_p L^2} = \frac{EI\pi^4 + \beta L^4}{4\pi\beta L^4} \tag{12}$$

And for a YSZ-ceramic-seal coating of $t = 0.038$ cm (0.015 in.) with a modulus $E = 34.5$ GPa (5×10^6 psi), on an inconel substrate of modulus $B = 207$ GPa

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*The deflection can also be represented by other functions as

$$w = a_2 \left\{ 1 - \cosh\left[a\,(a - 2x/L)\right]/\cosh\,(a) \right\} \quad a \geq 1$$

However, the energy integral over L is 6 times larger, and since we want the minimum energy the sine function was selected.

(3×10^7 psi), a pulloff stress σ_p = 9 MPa (1300 psi) acting on a unit width and assuming L = 0.625 cm (0.25 in.), the load P = 2.67 kN (600 lb_f); for t = 0.038 cm (0.015 in.), this represents a compressive stress of 0.2 GPa (29 ksi). With the application of compressive stress σ_c greater than $\sigma_c{}^*$, the coating will fail.

During the transient phase, significant thermal gradients occur and loading on the ceramic shifts toward the surface. The end moments approach Pt and failure can occur at half the above calculated compressive stress or,

$$\sigma_c > \frac{\sigma_c^*}{2} \tag{13}$$

Thus it has been demonstrated that a possible mechanism of ceramic seal failure is pulloff induced by compressive load, the sources of which have already been cited.

OBSERVED FAILURES AND TESTS

Pulloff of Cylindrical Specimens

The failure of cylindrical test specimens run in a Mach 0.3 Jet-A/air burner is well documented (ref. 1) and occur near the center of the specimen. In these tests, the specimens are hotter in the central portion of the cylinder than near the ends which are cooled on one end by radiation plus convection and by a heat sink on the other. In all cases noted, delamination is exfoliation of the ceramic and occurs near the center and on the surface facing other hot cylinders.

Shear Failure near Edges

Although the delamination of flat specimens is commonplace (ref. 5) values for the delamination length and separation of the effects of shear and bending

can not be made without shear stress data. Finding no suitable values in the literature, we performed some tests to define a range of shear stress values.

Experimental Shear Tests

To determine some relative values of shear stress for the ZrO_2-Y_2O_3/NiCrAlY/substrate, several simple tests were conducted. In one, a plasma sprayed inconnel rod which had been run to term in a burner test was potted within a stainless steel nipple using epoxy, figure 4. The uncoated portion of the specimen was clamped and the assembly torqued to failure of the plasma sprayed material, see figure 5. Assuming uniform distribution of shear stress with homogeneous bonding, the applied torque is,

$$T = \int \tau r dA \tag{14}$$

Failure of the ceramic occured at a torque of 198 N-m (1755 in-lb_f) and solving, the maxium shear stress of the ceramic (after burner testing) becomes,

$$\tau_{v,max} = 15.5 \text{ MPa (2250 psi)} \tag{15}$$

In another test series, two stainless tubes (1.27 cm diameter (O.D.) x 0.089 cm wall x 25.4 cm long) (0.5 x 0.035 x 10 in.) were plasma sprayed over a 7.6 cm (3 in.) length in the center of the tube with ZrO_2-Y_2O_3 to thicknesses of 0.076 cm (0.030 in.) and 0.038 cm (0.015 in.), figure 6. The specimens were clamped and torqued until the ceramic failed. Failure first occured near the clamped end and spread across the sprayed area. The 0.076 cm (0.030 in.) material split longitudinally and completely delaminated, figure 5. At the applied critical torque, the 0.038 cm (0.015 in.) plasma sprayed material became unstable and cracks spread at nearly a uniform rate along and

around the cylinder in a sprial manner, but the coating remained attached in several places. Such behavior underscores the importance of thickness in bond strength.

Assuming a uniformly sprayed composite system, the governing strain relations become,

$$\left(\frac{T}{\theta}\right) = \sum G_i J_i \tag{16}$$

$$\theta = \frac{\tau_j}{G_j r_j} \tag{17}$$

For a composite tube of ceramic, bondcoat, and substrate,

$$\sum G_i J_i = \frac{E_s}{2(1 + \nu_s)}\left[\left(r_2^4 - r_1^4\right) + \frac{E_B}{E_s}\,\frac{1 + \nu_s}{1 + \nu_B}\left(r_3^4 - r_2^4\right) + \frac{E_c}{E_s}\,\frac{1 + \nu_s}{1 + \nu_c}\left(r_4^4 - r_3^4\right)\right] \tag{18}$$

$$\tau\nu_{ic} = \frac{TG_c\, r_3}{\sum G_i J_i} \tag{19}$$

As the failures occured at the bondcoat-ceramic interface, the radius r_3 is used to calculate the shear stress at failure. The system became unstable at an applied torque of 46 N-m (410 in-lb), providing

$$\tau_{v,max} = 37 \text{ MPa } (5370 \text{ psi})$$

A similar value was determined for the 0.076 cm (0.030 in.) thickness, but the instability of the fracture was not observed in detail.

These simple tests provide some comparison between pre- and post-test shear magnitudes. Although both experiments can be criticised for lack of detail, the first also suffers from the assumption of uniform shear and thick porous ceramics are sensitive to initial crack distributions. A reduction in overall loading by a factor of 2 to 4 has been noted when 'point regions' are loaded and fail in a sequential manner than when the loading is applied and distributed uniformly over the surface (refs. 6 and 7). While it should follow that post-test shear magnitudes would be less than pretest values, nonuniform shear loading effects would mitigate the differences.

CONCLUSIONS

When ceramics on metal substrates, for potential use as high temperature seals or other applications, are exposed to forces originating from differences in thermal expansion between the ceramic and the metal substrate delamination can occur. For plate or sheet type specimens, edge delamination can occur due to shear between the ceramic and the substrate. For specimens where tensile stresses are developed when bending is produced in the ceramic, pulloff stress becomes the mode of failure. Thus shear is associated with stress concentration near the edges of the component while bending is more associated with the distortion of a region near the central portion of the specimen. Both modes are significant in predicting life of the ceramic.

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SYMBOLS

A	area
a	parameter for the cosh function
$a_{1,2}$	constants
E	modulus of elasticity
I	moment of inertia
J	torsional moment of inertia
L	length
P	applied load
r	radius
T	temperature
Tq	torque
t	thickness
W	width
w	deflection
x,y	coordinate directions
α	thermal expansion
β	substrate 'spring' constant uniform load
δ	increment
σ	normal stress
τ	shear stress
θ	angular displacement
ν	Poisson's ratio

Subscripts

B	bondcoat
c	ceramic, compression
i,j	material indices
max	maximum
p	pulloff
s	substrate
t	tension
v	shear
1,2,3,4	reference radii

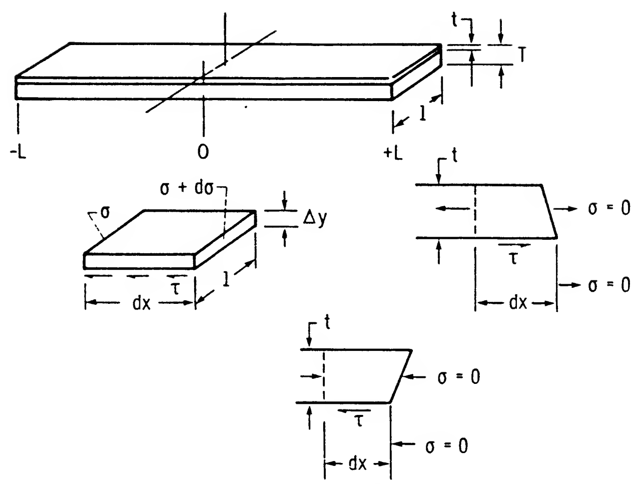

Figure 1. - Shear-free body diagrams.

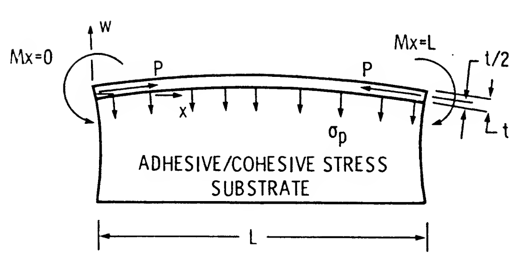

Figure 2. - Schematic of bending stresses due to thermal compression.

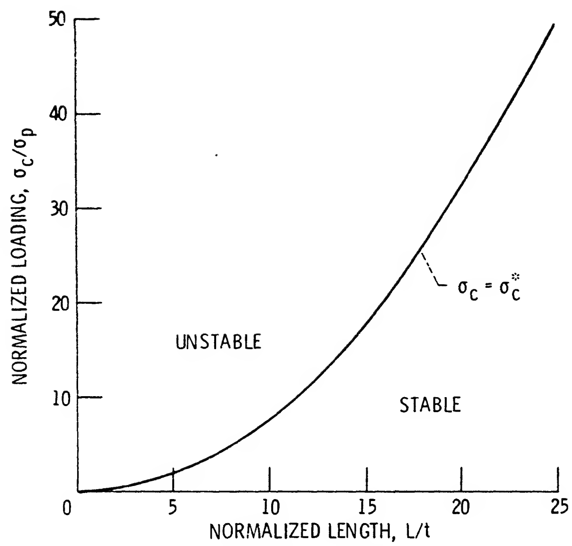

Figure 3. - Critical bending stresses due to thermal contraction as a function of length.

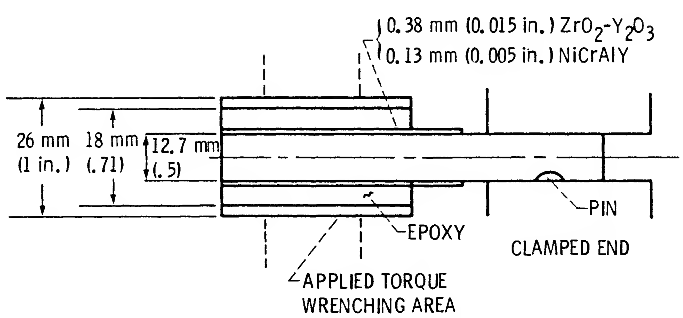

Figure 4. - Schematic of 'potted' cylinder torsion test specimen.

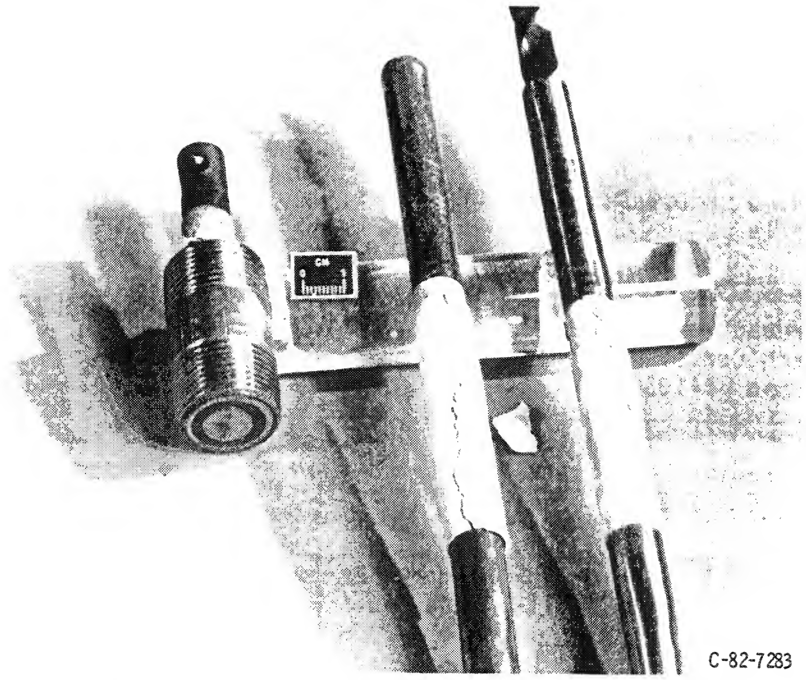

Figure 5. - Photograph of test specimens failed in torsion.

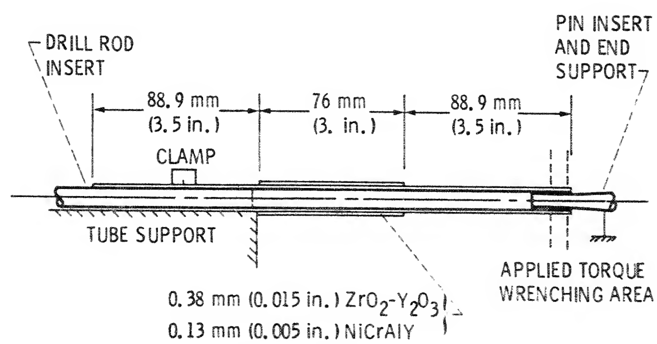

Figure 6. - Schematic of tubes with plasma sprayed ZrO_2-Y_2O_3 torsion test specimen.

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15. Supplementary Notes

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16. Abstract

Ceramics on metal substrates for potential use as high temperature seals or other applications are exposed to forces originating from differences in thermal expansion between the ceramic and the metal substrate. This report develops a relationship between the difference in expansion of the ceramic and the substrate, defines conditions under which shear between the ceramic and the substrate occurs, and those under which bending forces are produced in the ceramic. The off-axis effect of compression forces resulting from high temperature plastic flow of the ceramic producing buckling of the ceramic is developed. Shear is associated with the edge or boundary stresses on the component while bending is associated with the distortion of an interior region. Both modes are significant in predicting life of the ceramic.

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